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(54) Title: MULTIPLE ASM OBIGGS WITH DIFFERENT PERMEABILITY AND SELECTIVITY MEMBRANES

(57) Abstract

A method and system for providing nitrogen-enriched air (NEA) to aircraft fuel tanks using multiple air separation modules (ASMs). The ASMs employ membranes having different permeabilities and selectivities which are particularly selected to meet the varying NEA needs of the fuel tanks during flight.

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# MULTIPLE ASM OBIGGS WITH DIFFERENT PERMEABILITY AND SELECTIVITY MEMBRANES

## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

The present invention generally relates to a method and system for inerting aircraft fuel tanks. The invention particularly relates to a method and system for providing nitrogen-enriched air (NEA) to aircraft fuel tanks using multiple air separation modules (ASMs). The ASMs employ membranes having different permeabilities and selectivities which are particularly selected to meet the varying NEA needs of the aircraft performance requirements.

### 2. Description of the Related Art

It is generally recognized that fuel vapors in an enclosed area such as a fuel tank may result in flame propagation or even an explosion if sufficient oxygen is present. The threat of an explosion, however, can be substantially reduced if the oxygen concentration in the fuel tank is lowered to 9% by volume or less.

Due to the risk of an explosion, some vehicles, particularly aircrafts, have been equipped with on-board inert gas generating systems (OBIGGS). The OBIGGS are intended to provide a supply of nitrogen or nitrogen-enriched gas to fill the vapor space or ullage in the fuel tank in order to lower its oxygen content and thereby reduce the possibility of an explosion.

Various OBIGGS have been proposed in the art. However, there remains a continuing need in the art for OBIGGS that have reduced size, weight, and operating cost, but yet can provide a sufficient amount and purity of NEA to inert, for example, aircraft fuel tanks during a variety of different operating conditions.

## SUMMARY OF THE INVENTION

The present invention is intended to address this need in the art. It takes particular advantage of the fact that an aircraft has varying inert gas requirements during the course of its flight. For example, during level altitude or cruising, a relatively low rate of NEA flow is required to replace the fuel being used. During a descent maneuver such as landing, a higher rate of NEA flow is required to keep the internal pressure in the fuel tanks equal to the external pressure to minimize the in-rush of 21% by volume $O_2$ air and to maintain the ullage oxygen concentration at 9% by volume or lower. Likewise, during an ascent maneuver such as takeoff, a higher flow rate of NEA is required to inert the fuel tanks because of the evolution of dissolved $O_2$ from the fuel due to the drop in the atmospheric pressure.

Briefly, the present invention employs multiple gas separation modules which contain membranes having different permeabilities and selectivities to separate compressed air into NEA. The membrane modules are advantageously selected to provide the NEA required to inert the aircraft fuel tanks based on the aircraft's particular performance requirements, while minimizing the system's overall size, weight, and operating cost.

More particularly, in its first aspect, the present invention relates to a method for inerting an aircraft fuel tank. The method comprises the steps of:

(a) contacting compressed air with one or more first membrane modules at conditions effective to produce a first nitrogen-enriched air stream;

(b) introducing the first nitrogen-enriched air stream into the fuel tank during periods of low demand for nitrogen-enriched air;

(c) contacting compressed air with one or more second membrane modules at conditions effective to produce a second nitrogen-enriched air stream; and

(d) introducing the second nitrogen-enriched air stream into the fuel tank during periods of high demand for nitrogen-enriched air. The first membrane modules have a lower $O_2$ permeance and a higher $O_2/N_2$ selectivity than the second membrane modules.

In its second aspect, the present invention relates to a system for inerting an aircraft fuel tank. The system comprises:

(a) one or more first membrane modules for separating compressed air into a first permeate stream comprising oxygen-enriched air and a first retentate stream comprising nitrogen-enriched air;

(b) a first conduit for conveying the first retentate stream into the fuel tank during periods of low demand for nitrogen-enriched air;

(c) one or more second membrane modules for separating compressed air into a second permeate stream comprising oxygen-enriched air and a second retentate stream comprising nitrogen-enriched air; and

(d) a second conduit for conveying the second retentate stream into the fuel tank during periods of high demand for nitrogen-enriched air. The first membrane modules have a lower $O_2$ permeance and a higher $O_2/N_2$ selectivity than the second membrane modules.

As used herein, the "periods of low demand for nitrogen-enriched air" refer to instances when the volumetric output of the one or more first membrane modules can produce enough NEA to maintain the oxygen concentration in the ullage of the aircraft fuel tank below the explosive limit, which is currently believed to be about 9% by volume or less. An example of such a period includes while the aircraft is cruising or is maintaining a level altitude.

On the other hand, the "periods of high demand for nitrogen-enriched air" refer to instances when the volumetric output of the one or more first membrane modules cannot produce enough NEA to maintain the oxygen concentration in the ullage of the aircraft fuel tank below the explosive limit. Such periods include during ascent, descent, and mid-air refueling.

## DETAILED DESCRIPTION OF THE INVENTION

During level altitude or the cruising phase of an aircraft's flight, less NEA is required to maintain the oxygen concentration in the ullage of a fuel tank below the explosive limit. Thus, it is possible to use more energy efficient, higher performance membrane modules to supply the required NEA.

Accordingly, during periods of low NEA demand, compressed air is contacted with one or more first membrane modules at conditions effective to produce a first NEA stream. The compressed air can be from any source on board the aircraft such as engine bleed air, bleed air from the aircraft's environmental control system, or air from an independent compressor. Regardless of the source of the compressed air, it typically contains about

21% by volume $O_2$, 78% by volume $N_2$, and traces of Ar and other gases. The air, however, may have a lower oxygen concentration at higher altitudes.

There is a relationship between the compressed air pressure, which translates to the driving force across the membrane, and the number of membrane modules required to perform the desired separation, and thus the overall size and weight of the system. For example, it has been discovered that increasing the compressed air pressure from 30 psig (308.0 kPa) to 50 psig (445.8 kPa) can reduce the module weight as well as its overall size by over 50%. Therefore, it is preferred that the compressed air has a pressure ranging from 10 psig (170.2 kPa) to 300 psig (2168.3 kPa), and more preferably, from 20 psig (239.1 kPa) to 100 psig (790.3 kPa). The driving force across the membrane can also be effected or enhanced by applying a vacuum on the permeate side of the membrane.

The first membrane modules contain a membrane material that preferentially permeates oxygen and retains nitrogen. In addition, they are advantageously selected to have a lower $O_2$ permeance and a higher $O_2/N_2$ selectivity than the second membrane modules. Preferably, the first membrane modules are selected to have an $O_2$ permeance of at least 10 GPU ($10^{-6}$ $cm^3/cm^2 \cdot sec \cdot cm\text{-}hg$) and an $O_2/N_2$ selectivity of at least 4.0 measured at operating conditions. More preferably, the first membrane modules have an $O_2$ permeance of at least 30 GPU ($10^{-6}$ $cm^3/cm^2 \cdot sec \cdot cm\text{-}hg$) and an $O_2/N_2$ selectivity of at least 5.0.

Membrane modules having such properties are known in the art. They are generally referred to as high performance membranes. For example, but without limitation, the membrane material in the first modules can be made of cellulose derivatives, polyamides, polyimides, polyamide-imides, polysulfones, copolymers and blends thereof.

The membrane material is preferably in the form of asymmetric or composite hollow fibers, but may be in roll form, and plate and frame cartridges. More preferably, the first membrane modules contain hollow fibers described in one of U.S. Patent Nos. 4,230,463; 4,983,191; 5,015,270; 5,085,676; and 5,096,468, and EP 0 207 721 A2; the contents of which are hereby incorporated by reference.

The temperature of the compressed air and/or the membrane has an affect on the permeability and selectivity of the membrane modules. For example, for a given compressed air flow rate and pressure, the permeability of the membrane can increase as the temperature increases. Thus, it is preferable to contact the compressed air with the first membrane modules at a temperature ranging from 0°C to 100°C, and preferably from 0°C to 80°C. Of course, the compressed air can be heated prior to the contacting step in order to maximize the productivity of the membrane modules.

The flow rate of the compressed air to the first membrane modules can vary, depending on the particular NEA requirements of the aircraft fuel tanks. Generally, however, the flow rate of the compressed air into the first membrane modules should be sufficient to provide enough NEA to the fuel tanks to maintain an oxygen concentration in the ullage space below the explosive range, i.e., 9% by volume $O_2$ or less, during periods of low demand such as cruising.

The first NEA stream preferably has a flow rate of 0.05 lbs/ min (0.023 kg/min) to 20 lbs/min (9.091 kg/min) and an oxygen content of 9% by volume or less. More preferably, the first NEA stream has a flow rate of 0.5 lbs/min (0.227 kg/min) to 2.0 lbs/min (0.909 kg/min) and an oxygen content of 5% by volume or less. The first NEA stream is advantageously introduced into the fuel tank of an aircraft during periods of low

NEA demand to maintain the oxygen content in the ullage of the fuel tank below the explosive range.

During certain flight maneuvers such as ascent and descent, the first membrane modules may not be able to provide sufficient NEA flow to the aircraft's fuel tank to maintain the oxygen concentration in the ullage below the explosive limit. Thus, it would be advantageous to employ less efficient, but higher productivity membrane modules to supply the required NEA.

Like the first membrane modules, the second membrane modules contain a membrane material that preferentially permeates oxygen and retains nitrogen. The membrane material in the second modules, however, is preferably highly permeable so as to fulfill the high demand of NEA during flight periods such as ascent and descent.

The second membrane modules preferably have an $O_2$ permeance of at least 100 GPU ($10^{-6}$ $cm^3/cm^2 \cdot sec \cdot cm\text{-}hg$) and an $O_2/N_2$ selectivity of at least 1.5 measured at operating conditions. More preferably, the second membrane modules have an $O_2$ permeance of at least 200 GPU ($10^{-6}$ $cm^3/cm^2 \cdot sec \cdot cm\text{-}hg$) and an $O_2/N_2$ selectivity of at least 2.0. These membrane modules are usually referred to as having ultra high permeability.

Various such membrane materials are known in the art. For example, but without limitation, cellulose derivatives, polyamides, polyimides, polyamide-imides, polysulfones, copolymers and blends thereof have been found to be useful. The membrane materials are preferably in the form of asymmetric or composite hollow fibers, but may be in roll form, and plate and frame cartridges. More preferably, the second membrane modules contain

hollow fibers described in one of U.S. Patent Nos. 4,717,394; 5,034,024; and 5,051,114, and EP 0 207 721 A2; the contents of which are hereby incorporated by reference.

The compressed air can be contacted with the second membrane modules at the same general conditions as it is contacted with the first membrane modules. However, because more NEA is needed to fill the ullage space during high NEA demand periods, the second NEA stream generally, but not necessarily has a higher flow rate and a higher oxygen content than the first NEA stream.

The second NEA stream preferably has a flow rate of 5 lbs/min (2.273 kg/min) to 100 lbs/min (45.455 kg/min) and an oxygen content of 9% by volume or less. More preferably, the second NEA stream has a flow rate of 10 lbs/min (4.545 kg/min) to 50 lbs/min (22.727 kg/min). This second NEA stream is advantageously introduced into the fuel tank of an aircraft during periods of high NEA demand such as ascent and descent to maintain the oxygen content in the fuel tank below the explosive limit.

The second NEA stream can be introduced into the fuel tank in combination with or in lieu of the first NEA stream, depending on the particular NEA requirements of the aircraft at the time. To minimize energy consumption, one or more of the membrane modules in each set may be turned off when the NEA from those modules is not required to meet the demand of the aircraft.

Moreover, either one or both of the first and second NEA streams can be introduced directly into the liquid fuel in the fuel tank, such as through a bubbler, to scrub or remove dissolved $O_2$ from the fuel. Preferably, the first NEA stream is introduced into the liquid fuel. As those skilled in the art will readily appreciate, such an embodiment can reduce the risk of an explosion even further.

For both sets of membrane modules, if more than one is employed in each set, the modules in each set can be arranged in series and/or in parallel. If employed in series, the NEA retentate stream of one module can be used as a feed to another module in that set. In addition, either the permeate stream or the retentate stream or both can be recycled to a previous module to maximize the separation efficiency of the modules.

In its second aspect, the present invention relates a system for carrying out the above-described process. The system contains two sets of membrane modules for separating compressed air into a permeate stream comprising oxygen-enriched air and a retentate stream comprising nitrogen-enriched air. Each set has a different permeability and selectivity. In particular, the first set of membrane modules is selected to have a lower $O_2$ permeance, but a higher $O_2/N_2$ selectivity than the second set of membrane modules.

Preferably, the first membrane modules have an $O_2$ permeance of at least 10 GPU ($10^{-6}$ $cm^3/cm^2 \cdot sec \cdot cm\text{-}hg$) and an $O_2/N_2$ selectivity of at least 4.0, and the second membrane modules have an $O_2$ permeance of at least 100 GPU ($10^{-6}$ $cm^3/cm^2 \cdot sec \cdot cm\text{-}hg$) and an $O_2/N_2$ selectivity of at least 1.5. More preferably, the first membrane modules have an $O_2$ permeance of at least 30 GPU ($10^{-6}$ $cm^3/cm^2 \cdot sec \cdot cm\text{-}hg$) and an $O_2/N_2$ selectivity of at least 5.0, and the second membrane modules have an $O_2$ permeance of at least 200 GPU ($10^{-6}$ $cm^3/cm^2 \cdot sec \cdot cm\text{-}hg$) and an $O_2/N_2$ selectivity of at least 2.0.

Both sets of membrane modules contain a compressed air inlet and an NEA stream outlet. Each NEA stream outlet is connected to a conduit which is provided to convey the NEA stream from the membrane modules to the ullage of the aircraft fuel tank. Each outlet can be connected to a separate conduit. Alternatively, the outlets can be connected to a common conduit which carries the NEA into the fuel tank as needed. The system can

also contain a third conduit for introducing the first NEA stream or the second NEA stream or both into the liquid fuel in the aircraft fuel tank in order to liberate at least a portion of $O_2$ dissolved in the fuel.

The first membrane modules and the second membrane modules can be arranged in a bundle-in-bundle configuration as described in U.S. Patent No. 5,013,331; the content of which is hereby incorporated by reference. For example, one first membrane module can be arranged as the outer bundle while one second membrane module can be the inner bundle. Such an arrangement can provide significant reductions in the overall size and weight of the system.

While the invention has been described with reference to preferred embodiments, it is to be understood that variations and modifications may be resorted to as will be apparent to those skilled in the art. Such variations and modifications are to be considered within the purview and scope of the invention as defined by the claims appended hereto.

WHAT IS CLAIMED IS:

1. A method for inerting an aircraft fuel tank, said method comprising the steps of:

(a) contacting compressed air with one or more first membrane modules at conditions effective to produce a first nitrogen-enriched air stream;

(b) introducing said first nitrogen-enriched air stream into said fuel tank during periods of low demand for nitrogen-enriched air;

(c) contacting compressed air with one or more second membrane modules at conditions effective to produce a second nitrogen-enriched air stream; and

(d) introducing said second nitrogen-enriched air stream into said fuel tank during periods of high demand for nitrogen-enriched air,

wherein said first membrane modules have a lower $O_2$ permeance and a higher $O_2/N_2$ selectivity than said second membrane modules.

2. The method according to claim 1, wherein said low demand periods include cruising.

3. The method according to claim 1, wherein said high demand periods include ascent or descent or both.

4. The method according to claim 1, further comprising introducing at least one of said first nitrogen-enriched air stream and said second nitrogen-enriched air stream

into the fuel in said fuel tank at conditions effective to liberate at least a portion of dissolved $O_2$ in the fuel.

5. The method according to claim 4, wherein said first nitrogen-enriched air stream is introduced into the fuel in the fuel tank to liberate at least a portion of dissolved $O_2$ in the fuel.

6. The method according to claim 1, wherein said first nitrogen-enriched air stream has a lower flow rate than said second nitrogen-enriched air stream.

7. The method according to claim 1, wherein said first nitrogen-enriched air stream has a flow rate of 0.05 to 20 lbs/min at 9% by volume $O_2$ or less, and said second nitrogen-enriched air stream has a flow rate of 5 to 100 lbs/min at 9% by volume $O_2$ or less.

8. The method according to claim 7, wherein said first nitrogen-enriched air stream has a flow rate of 0.5 to 2.0 lbs/min at 5% by volume $O_2$ or less, and said second nitrogen-enriched air stream has a flow rate of 5 to 50 lbs/min at 9% by volume $O_2$ or less.

9. The method according to claim 1, wherein said first membrane modules have an $O_2$ permeance of at least 10 GPU and an $O_2/N_2$ selectivity of at least 4.0, and said second membrane modules have an $O_2$ permeance of at least 100 GPU and an $O_2/N_2$ selectivity of at least 1.5.

10. The method according to claim 9, wherein said first membrane modules have an $O_2$ permeance of at least 30 GPU and an $O_2/N_2$ selectivity of at least 5.0, and said second membrane modules have an $O_2$ permeance of at least 200 GPU and an $O_2/N_2$ selectivity of at least 2.

11. The method according to claim 1, wherein said compressed air comprises bleed air.

12. The method according to claim 1, wherein said compressed air has a pressure of 10 to 300 psig.

13. The method according to claim 1, which comprises introducing said first nitrogen-enriched air stream and said second nitrogen-enriched air stream into said fuel tank during periods of high demand for nitrogen-enriched air.

14. A method for inerting an aircraft fuel tank, said method comprising the steps of:

(a) contacting compressed air with one or more first membrane modules at conditions effective to produce a first nitrogen-enriched air stream;

(b) introducing said first nitrogen-enriched air stream into said fuel tank during cruising;

(c) contacting compressed air with one or more second membrane modules at conditions effective to produce a second nitrogen-enriched air stream; and

(d) introducing said second nitrogen-enriched air stream into said fuel tank during ascent or descent or both,

wherein said first membrane modules have a lower $O_2$ permeance and a higher $O_2/N_2$ selectivity than said second membrane modules.

15. The method according to claim 14, further comprising introducing at least one of said first nitrogen-enriched air stream and said second nitrogen-enriched air stream into the fuel in said fuel tank at conditions effective to liberate at least a portion of dissolved $O_2$ in the fuel.

16. The method according to claim 15, wherein said first nitrogen-enriched air stream is introduced into the fuel in the fuel tank to liberate at least a portion of dissolved $O_2$ in the fuel.

17. The method according to claim 14, wherein said first nitrogen-enriched air stream has a lower flow rate than said second nitrogen-enriched air stream.

18. The method according to claim 14, wherein said first nitrogen-enriched air stream has a flow rate of 0.05 to 20 lbs/min at 9% by volume $O_2$ or less, and said second nitrogen-enriched air stream has a flow rate of 5 to 100 lbs/min at 9% by volume $O_2$ or less.

19. The method according to claim 18, wherein said first nitrogen-enriched air stream has a flow rate of 0.5 to 2.0 lbs/min at 5% by volume $O_2$ or less, and said second nitrogen-enriched air stream has a flow rate of 5 to 50 lbs/min at 9% by volume $O_2$ or less.

20. The method according to claim 14, wherein said first membrane modules have an $O_2$ permeance of at least 10 GPU and an $O_2/N_2$ selectivity of at least 4.0, and said second membrane modules have an $O_2$ permeance of at least 100 GPU and an $O_2/N_2$ selectivity of greater than 1.5.

21. The method according to claim 20, wherein said first membrane modules have an $O_2$ permeance of at least 30 GPU and an $O_2/N_2$ selectivity of at least 5.0, and said second membrane modules have an $O_2$ permeance of at least 200 GPU and an $O_2/N_2$ selectivity of at least 2.

22. The method according to claim 14, wherein said compressed air comprises bleed air.

23. The method according to claim 14, wherein said compressed air has a pressure of 10 to 300 psig.

24. The method according to claim 14, which comprises introducing said first nitrogen-enriched air stream and said second nitrogen-enriched air stream into said fuel tank during ascent or descent or both.

25. A system for inerting an aircraft fuel tank, said system comprising:

(a) one or more first membrane modules for separating compressed air into a first permeate stream comprising oxygen-enriched air and a first retentate stream comprising nitrogen-enriched air;

(b) a first conduit for conveying said first retentate stream into said fuel tank during periods of low demand for nitrogen-enriched air;

(c) one or more second membrane modules for separating compressed air into a second permeate stream comprising oxygen-enriched air and a second retentate stream comprising nitrogen-enriched air; and

(d) a second conduit for conveying said second retentate stream into said fuel tank during periods of high demand for nitrogen-enriched air,

wherein said first membrane modules have a lower $O_2$ permeance and a higher $O_2/N_2$ selectivity than said second membrane modules.

26. The system according to claim 25, further comprising a third conduit for introducing at least one of said first retentate stream and said second retentate stream into the fuel in said fuel tank to liberate at least a portion of dissolved $O_2$ in the fuel.

27. The system according to claim 25, wherein said first membrane modules have an $O_2$ permeance of at least 10 GPU and an $O_2/N_2$ selectivity of at least 4.0, and said second membrane modules have an $O_2$ permeance of at least 100 GPU and an $O_2/N_2$ selectivity of at least 1.5.

28. The system according to claim 27, wherein said first membrane modules have an $O_2$ permeance of at least 30 GPU and an $O_2/N_2$ selectivity of at least 5.0, and said second membrane modules have an $O_2$ permeance of at least 200 GPU and an $O_2/N_2$ selectivity of at least 2.

29. The system according to claim 25, wherein said first membrane modules and said second membrane modules are arranged in a bundle-in-bundle configuration.

30. The system according to claim 29, wherein said first conduit and said second conduit have common portions.